8. HIGH PERFORMING ACTUATION SYSTEM FOR USE WITH A LOUVER ARRAY FOR SATELLITE THERMAL CONTROL

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1.0 INTRODUCTION

To meet the more stringent thermal requirements of advanced spacecrafts of the European Space Research Organisation, ESRO, a high performing actuation system has been developed to drive one pair or a set of 9 pairs of louver blades. This under simulated space conditions successfully tested actuation system has, compared with a bimetal or bellows actuator, considerable advantages, i.e.:

- high sensitivity, approx. 0.2 °C
- small ΔT range between opened and closed blades, 5 °C ± 1 °C
- faster response for finer temperature control, approx. 5 sec at a ΔT = 5 °C
- easy adaption to hot spot sensing for localised high dissipating equipment
- the system can be developed into a moderately high torque actuator

A bimetal actuator, for instance, is very simple and reliable but it shows the following performance limitations:

- sensitivity limited to ~3 °C
- ΔT range between fully opened and closed positions of the blades has to be 15 °C or more
- no possibility of controlling hot spots
- long time constant

2.0 SUMMARY

The high performance actuation system uses a Bourdon spiral as the driving member (see fig. 1).

A tank filled with dimethylether ($C_4H_{10}O$) having a high coefficient of volumetric expansion is used as a temperature sensing and actuating medium. As the tank temperature increases, the pressure of the liquid also increases , and is directly transmitted through a capillary to the Bourdon spiral. Tank, connecting capillary, Bourdon spiral and overpressure compensator constitute a closed system. The angle of rotation of the center of the Bourdon spiral is proportional to the pressure, or the temperature.

The prototype was designed to give an angle of rotation of 90 °, with a temperature change of 5 °C ± 1 °C. (Sensitivity: 18 angular degrees per 1 °C. A bimetal spiral gives approximately 6 angular degrees per 1 °C.) A mechanical set point variation device permits covering 3 operating ranges of 5 °C each.

The response time of the liquid expansion of the spiral system is in the order of three seconds. The system can be subjected to very high and low extreme temperatures (freezing point of ether -116 °C up to +70 °C). An overpressure compensator has been developed; this consists of a spring preloaded bellows (see fig. 2). A change of the spring constant of the spring-bellows assembly allows minimizing the pressure build-up above the operating temperature range. This device extends the upper limit of the non-operating temperature and it increases the overall reliability.

Besides the performance tests, qualification tests have been carried out, demonstrating that the actuation system withstands normal launching conditions. An operating life of 7 years with more than 7000 cycles can be expected because, in other fields, Bourdon tubes have demonstrated a very high reliability. Proper care has been taken not to introduce new materials and techniques. As far as soldering, brazing and welding are concerned, only well-known and tried processes have been employed.

The multiple blade actuator employs the same physical principle as the single blade actuator because it was felt it might be an advantage, with respect to performance and reliability, to employ the same actuation system to operate all 9 pairs of blades. A battery of separate tanks connected by heat conduction through the tank walls was chosen. This configuration gives a good heat conduction through the walls from tank to tank and shows a much better hot spot sensing capability than a mechanically coupled actuator.

3.0 DESIGN AND DEVELOPMENT OF THE ACTUATION SYSTEM

In order to find a suitable actuation system for a louver array as well as alternative solutions with the objective of highest mission success, selection procedures have been carried out to compare some typical configurations, including sensors, actuators, transmissions and bearings. The options were divided into two groups: electrical systems and pressure-expansion systems.

The goal of the study was to find a better system than the bimetal actuator.
The main evaluation parameters of the developed actuation system were:

performance

reliability

cost

Although the rating of the parameters used to compare the various systems may be somewhat subjective, the following conclusions can be drawn:
Because the Bourdon spiral actuator shows a high sensitivity, simplicity and reliability, it seems to be the best choice. The central shaft acts as connection between the two louver blades. It is driven by the inner end of the Bourdon spiral. For the set point variation of the operating temperature, the shaft can be rotated relatively to the inner end of the Bourdon spiral and clamped in place by means of two set screws.

3.1 Actuation characteristics of the Bourdon spiral (see fig. 3)

The angle of rotation of the center of the Bourdon spiral is proportional to the pressure and therefore proportional to the mean temperature of the liquid inside the tank. Because the Bourdon spiral increases its volume under pressure, the tank volume has to be large enough to cover both the compressibility of the liquid and the volume increase of the Bourdon spiral. The tank was considered to be rigid.

The spiral is not able to rotate more than 300 ° but it should withstand a non-operating temperature of 50 °C, with a corresponding maximum system pressure of 36 kp/cm^2. A special spiral protection device (see fig. 2) is employed (spiral retainer) to prevent the spiral from over-stretching.

Development tests showed that the highest permissible pressure of 36 kp/cm^2 exists at about 45 °C, depending on the tank rigidity. Because the highest non-operating temperature is

50 °C, an overpressure compensator had to be incorporated. The final overpressure compensator, a spring preloaded bellows, actually extends the non-operating temperature up to 70 °C.

The basic set point temperature of the system can be changed by changing the mechanical preload angle and the corresponding filling temperature of the ether.

3.1.1 Some limiting parameters of the Bourdon spiral

(The calculation of Bourdon spirals is to be seen in ref. 1)

linear range, pressure	0 to 18 kp/cm^2
linear range, angle	0 to 210°
rupture pressure, without retainer	23 kp/cm^2
highest permissible pressure non-operating, with retainer	36 kp/cm^2
max. angle of rotation	300°
max. temperature range	16 2/3 °C
number of set point ranges	$\frac{300}{90} = 3\ 1/3$
temperature range (operating)	$\Delta T = 5$ °C
corresponding angle	90°
Preloading the system mechanically with 30° at the required undertemperature of 1 2/3 °C, one obtains	3 full operating ranges
typical set point ranges (for a filling at 18 1/3 °C)	20 - 25 °C 25 - 30 °C 30 - 35 °C

3.2 Tank development

The geometry of the tank has been optimized with respect to:

- static and dynamic requirements
- available space
- rigidity
- weight
- ratio between heat transfer surface and tank volume
- short heat path

There exists just enough space between the louver blades to fit a flat rectangular tank (see fig. 1) underneath the Bourdon spiral.

3.2.1 Tank volume V_o

The Bourdon spiral has to rotate 90° for an increase of ΔT = 5 °C ± 1 °C (blades from closed to open position). To build up the necessary pressure, the following criterion must be met:

$$V_r = V_{lt} - V_{ltp} > 0$$

The required tank volume V_o for one actuator system is:

$$V_o = \frac{1}{\varkappa \cdot p} \cdot a \cdot \Delta V_{lt} \cdot \left(\frac{1}{a} - 1\right)$$

V_o	tank volume (cm^3)
$\varkappa$	compressibility of liquid (1 cm^2/kp)
p	resulting pressure within the system
ΔV_{lt}	thermal expansion of liquid (cm^3); p = 1 kp/cm^2
a	ratio of volumes; V_{ltp} / V_{lt}
ΔV_{ltp}	expansion of liquid under temperature and pressure p (cm^3)
ΔV_r	relative expansion of liquid-tank (cm^3)

3.2.2 Stresses in a rectangular tank under internal pressure p

Pressure vessels in general are made of cylindrical or spherical shapes. In our case, the available space and heat flow considerations led to a rectangular tank. To increase the stiffness, a tension pin (see fig. 2) was mounted in the middle of the tank. This pin also increased the heat conduction into the liquid.

The bending stress in the tank wall is:

$$\sigma_b \propto c \cdot \frac{1}{t^2}$$

σ_b	bending stress (kp/cm^2)
c	constant = f (curvature of corners in the tank and ratio of length to width) (see, for example, ref. 2)
t	time

3.3 Mechanical interface problems between actuator, louver shaft and bearing friction

3.3.1 Statement of problem

The louver shaft is held in two end bearings. The bearings consist of a stationary Teflon bushing with a spherical bore and a rotating, straight cylindrical stainless steel bushing, fixed to the louver shaft. This bearing configuration allows even a bent louver shaft to turn freely.
In axial direction, the shaft is not held in these bearings.

The actuator is mounted in the center between the two end bearings, and it has to provide the axial bearing. The actuator forms a third point on the louver shaft, and this constraint gives rise to radial bearing reactions and undesirable friction forces in the bearings of the louver shaft.

The least friction is obtained by leaving the center bearings out. The following force, however, will remain:

The path of the driving end of the Bourdon spiral is not an ideal circle. This, together with the radial spring constant of the Bourdon spiral will give a radial force. However, it is well to note that the radial spring constant of the Bourdon spiral is very small and that the resulting forces will be small, too.
Under excess temperature the actuator would turn more than 90°. Because the pin in the louver shaft hits a stop after a motion of 90°, an excess torque is created in the louver shaft.

3.3.2 Bearing friction and torque characteristics

Under space flight conditions, the only force acting is the radial spring force of the not perfectly centered Bourdon spiral.

Friction radius of bearings	3.7 mm
Thermal deflection	1 mm
Offset of Bourdon spiral	1 mm
Radial spring constant of Bourdon spiral	10 p/mm
Friction coefficient of stainless steel on Teflon in high vacuum	0.2
The above parameters give a friction moment of	1.48 cm-p

The torque characteristics of the actuator are:

Torque	0.8 p-cm/°
Angle of rotation per 1 °C	18°/°C
Minimum sensitivity	< 0.5 °C
Resulting torque at 1 °C	14.40 p-cm
- Friction moment	- 1.48 p-cm
Excess driving torque	12.92 p-cm

4.0 THERMAL ANALYSIS

4.1 Response behavior and heat flow base-plate — tank

To obtain a good response behavior, the resistance of the heat paths must be as small as possible. The tank bottom area acts as a base-plate. The heat is mainly transferred by conductance and radiation. For the best heat transfer, one has to optimize the values for k, because the contact area A and (m • c) can be considered as given and constant.

k total thermal conductivity $\frac{\text{Watt}}{\text{m}^2 \cdot {}^\circ\text{C}} \equiv \frac{\text{kcal}}{\text{m}^2 \cdot {}^\circ\text{C} \cdot \text{hrs}}$ (see figures 4 and 5).

4.2 Sensitivity

Tests showed that the shaft of the Bourdon spiral starts to rotate after less than 3 seconds at a ΔT of 5 °C. During the first 3 seconds, the liquid receives the following heat quantity Q (cal.):

$$Q = V_0 \cdot \gamma \cdot c \cdot \Delta T \left[1 - e^{-\frac{k \cdot A}{V_0 \cdot \gamma \cdot c} \cdot t}\right]$$ Dynamic heat flow

γ specific gravity of ether

c specific heat of ether

The angle of rotation $\Delta\varphi$ of the Bourdon spiral is:

$$\Delta\varphi = \frac{c_1}{c_2} \cdot Q$$

$$c_1 = \frac{\Delta p}{\Delta Q} \quad ; \quad c_2 = \frac{\Delta p}{\Delta \varphi}$$

$$\Delta\varphi = \frac{1.88}{0.085} \cdot 0.28 = 6.19^\circ$$

4.3 Conclusion

The actuator has to overcome friction in the bearings and this friction leads to a phase shift of 3 sec$\rightarrow 6^{\circ}$. This delay corresponds to a temperature difference $\Delta T = 0.34\ ^{\circ}C$ of the liquid. This calculated sensitivity was confirmed during performance tests.

5.0 PERFORMANCE TESTS

The actuation system was integrated with the louver array and for testing purposes attached to a suitable heating-cooling plate.
To record the angular position, an electrical contact could be made on the end-stop of the bearing-housing. During the tests in the vacuum chamber a pressure of 5×10^{-8} torr was maintained. (See fig. 6.)

5.1 Conclusions

The tests showed:

- the response of the actuator is nearly instantaneous
- the system reacts at a variation of the sensed temperature of less than $0.5\ ^{\circ}C$
- a super isolation blanket covering the actuators is advisable, especially when the louver array is used for hot-spot sensing.

6.0 REFERENCES

1. Wüest, Walter: Die Berechnung von Bourdonfedern (The calculation of Bourdon tubes). VDI-Forschungshaft 489, Ausgabe B, Band 28, 1962
2. Roark, Raymond J.: Formulas for Stress and Strain, Mc Graw Hill, 1965, page 117

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June 14th, 1973

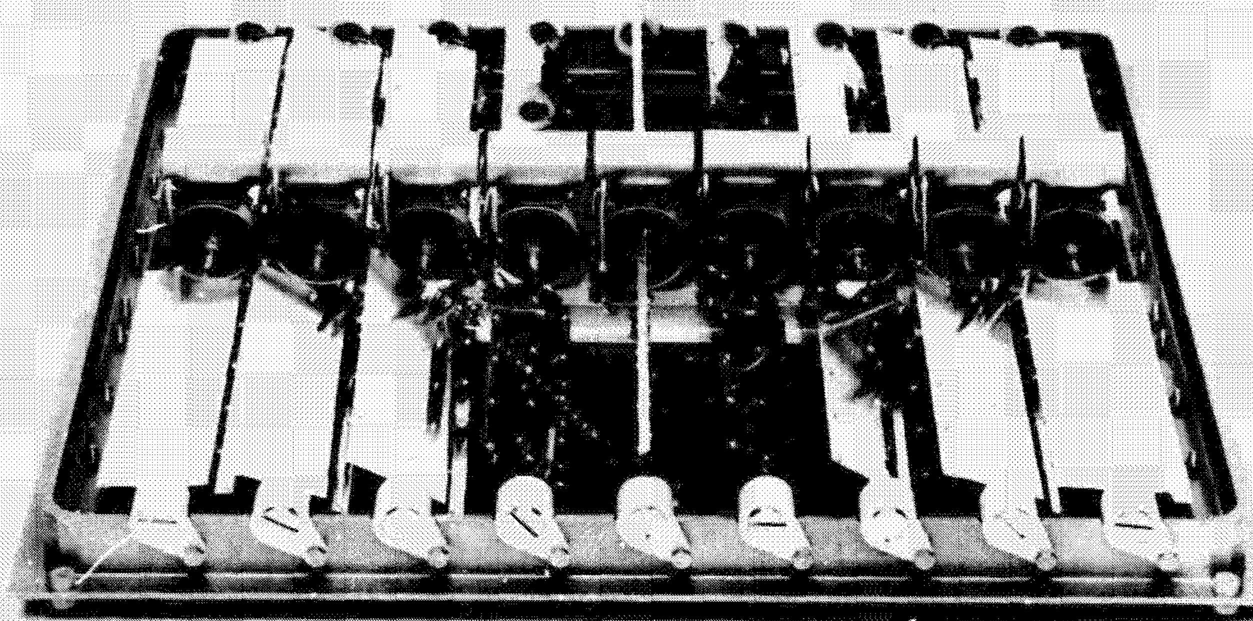

Figure 1.- Complete louver array with a high-performing actuation system.

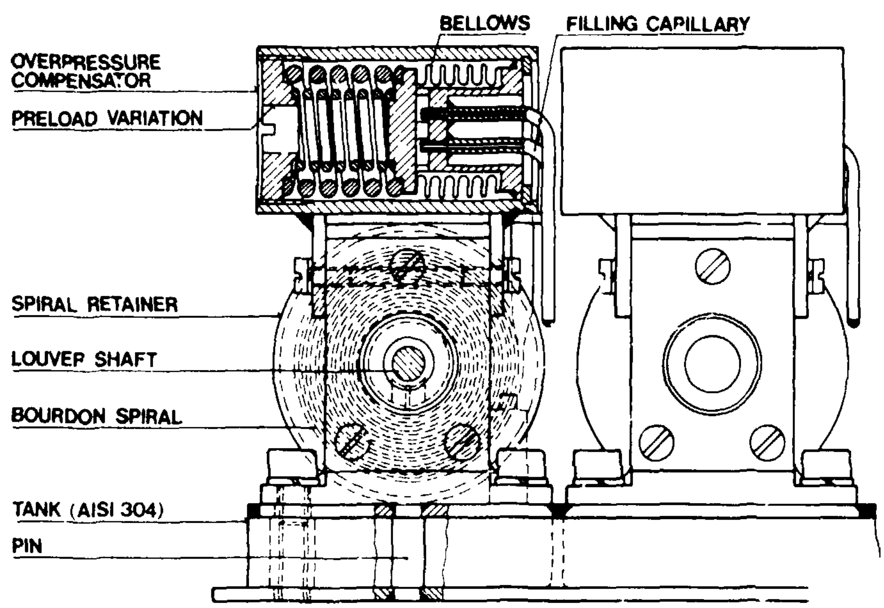

Figure 2.- Section of actuation system.

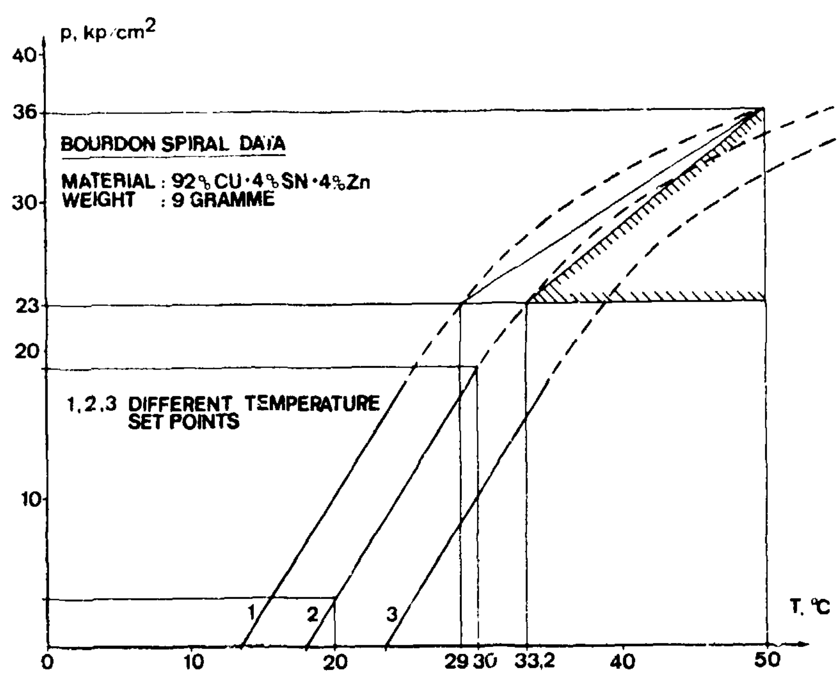

Figure 3.- Bourdon spiral. Temperature-pressure characteristics.

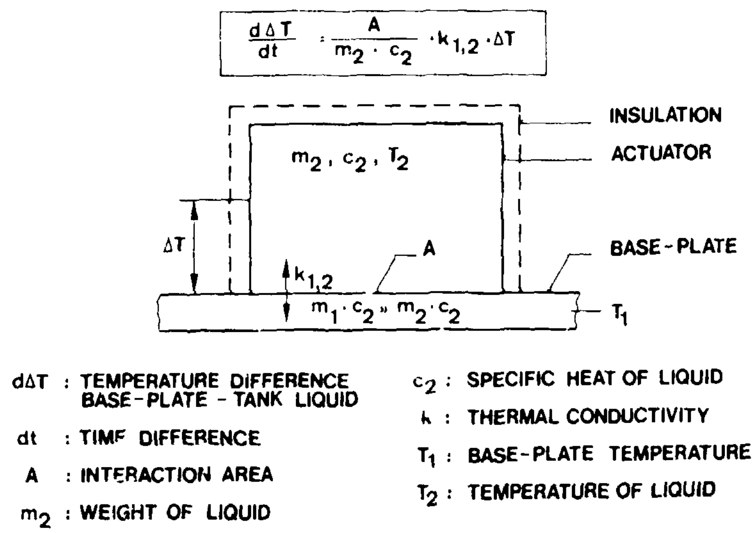

Figure 4.- Response behavior. Base-plate tank liquid.

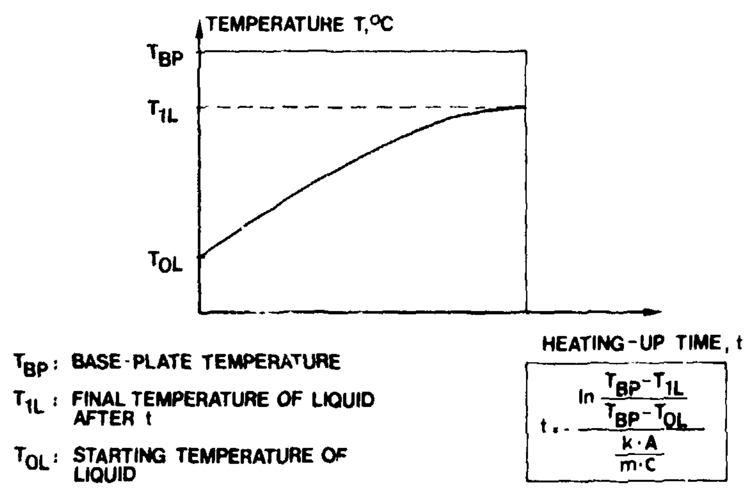

Figure 5.- Heat flow base-plate tank. Heating-up time.

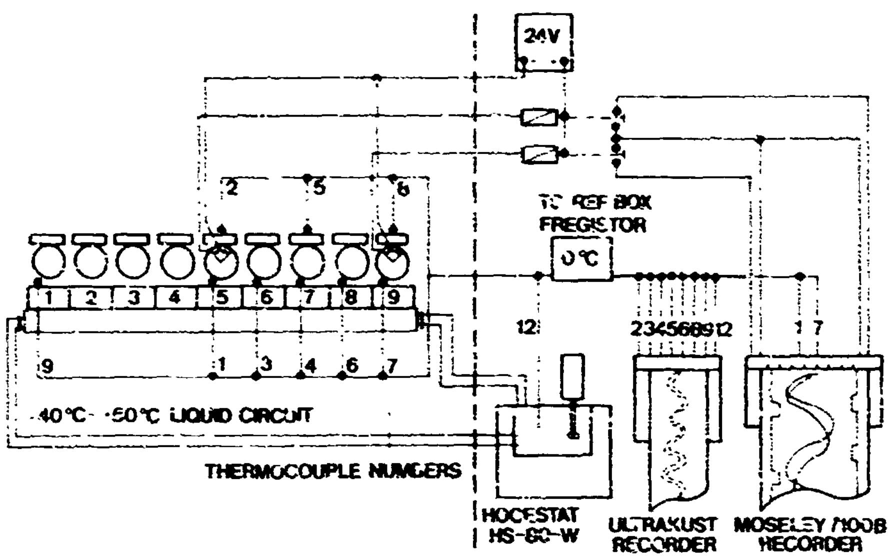

Figure 6. - Schematic diagram of the instrumentation during performance test.